DEPARTMENT OF DEFENCE
DEFENCE SCIENCE & TECHNOLOGY ORGANISATION

DSTO

Drag Reduction Technologies

V. – T. Truong

DSTO-GD-0290

20020108 144

Drag Reduction Technologies

V.-T. Truong

Maritime Platforms Division
Aeronautical and Maritime Research Laboratory

DSTO-GD-0290

ABSTRACT

Diluted polymer solutions, surfactants, microbubbles and compliant coating as drag reducers have been reviewed in this report. The advantages and disadvantages of each method have been discussed. For the polymer solutions, it is possible to achieve up to 80 % drag reduction with only a few parts per million of polymer. Ionic and non-ionic surfactants can also offer similar drag reduction as polymer solutions but at a high concentration of few percent. Microbubbles are perhaps the cheapest and non-polluted drag reducer. However, the control of the bubble size and the angle of ejection can impose technical challenges. This method can be combined with other drag reduction (DR) technologies such as polymers to enhance its effectiveness. Compliant coatings can be designed to behave in a similar fashion to the skin of a dolphin. The development of the compliant coating is theoretically complicated, although the optimized coating can offer a DR up to 50 %. Despite the extensive research in the area of DR over the past four decades, for each DR technology there is no universally accepted model that explains the DR mechanism. Application of DR technology with microbubbles to the ship hull indicated a 10 – 15 % reduction in drag. The full scale testing of a submarine by the US Navy has shown that polymer ejection has the potential to reduce the self-noise, drag and radiated noise generated by the propellor.

RELEASE LIMITATION

Approved for public release

DEPARTMENT OF DEFENCE
DEFENCE SCIENCE & TECHNOLOGY ORGANISATION **DSTO**

AQ F02-04-0466

Drag Reduction Technologies

Executive Summary

Turbulent flow in the boundary layer is the main source of submarine self-noise. This increases the submarine's acoustic signature and reduces the ability of the operators to resolve incoming signals against the background of the submarine self-noise. Drag reduction (DR) technologies offer several operational and tactical advantages for submarines, since DR delays the transition from laminar flow to turbulent flow, ie. suppresses turbulent flow, when speed is increased. DR technologies enable the maximization of the capability of the sonar systems and platform endurance, while retaining low acoustic self-signature.

There exist a number of drag reducers such as water-soluble polymers, surfactants, microbubbles or compliant coatings. It is possible to see up to 80 % DR with only few parts per million of added polymer. It has been established that polymers are the most effective drag reducers although other DR technologies have been proved to be effective. Application of DR technology with microbubbles to the ship hull indicated a 10 – 15 % reduction in drag. Full scale testing of a submarine has shown that polymer ejection not only will reduce the self-noise of a submarine, but also will offer DR and the radiated noise generates by the propeller.

While the USA, Russia, and Europe and Japan to a lesser extent, have been active in developing the DR technologies for application to ships and submarines for several decades, Australia is well behind those countries in the research area of DR. The US Navy is currently working on electromagnetic turbulence control (EMTC) tiles and fabrics to be attached to future submarines and torpedoes. The research of DR is theoretically and experimentally complicated and involves a wide range of disciplines including hydrodynamics, mathematics, physics, chemistry, materials science and engineering.

If proven beyond doubt that DR is required to enable the Collins class to do its current or near future prescribed role, it is desirable for a thorough analysis of the benefits and deficiencies of DR technologies to be conducted before DSTO considers research into these technologies. DSTO has the expertise to conduct such an analysis. MPD has a strong foundation in organic materials research that can provide essential knowledge on the use of polymers and surfactants as drag reducers. MOD and the Noise and Vibration group in MPD have developed techniques to monitor the noise and vibration from submarines. Research on the fluid dynamics of air and seawater has been conducted within AOD and MOD with specific application on aircraft and submarines. Antifouling has also been investigated in MPD. Collaboration with several rheology research groups in Australian universities and overseas research groups through TTCP and AAMOUR is essential in facilitating the research into DR.

Author

V.-T. Truong
Maritime Platforms Division

Tan Truong completed his Master of Engineering at Tokyo Institute of Technology (Japan) in 1977 and PhD at the University of Adelaide in 1980. He joined DSTO in 1987 and has worked on a number of research and development projects on organic materials for defence applications. He led a group to develop the use of electroactive polymers (EAP) as radar absorbing materials and corrosion protection coatings. He is currently investigating the potential use of EAP for sensors and actuators with applications in surface ship and submarines

Contents

1. Introduction

Turbulent flows can occur in the boundary layer near solid surfaces and the associated friction increases, as the flow velocity increases. The energy losses and self-noise due to turbulence friction can be of very high magnitude. This necessitates unabated research into drag reduction. The main purpose of drag reduction (DR) is to delay the onset of turbulent flows. In other words, a drag reducer will shift the transition from a laminar flow to a turbulent flow to higher flow velocity. In 1949, Toms [1] reported unusually low friction factors for dilute solutions of poly(methyl methacrylate) in monochlorobenzene. He was the first to publish drag reduction data which was later named as the "Toms effect". In the late fifties and early sixties, the effect of dilute polymer solutions on drag reduction was actively investigated. Possible defence application was initiated by the work of Pruitt and Crawford [2] and Savins [3]. Hoyt and coworkers [4-7] from U. S. Navy organizations have made significant contributions to the drag properties of the dilute solutions of poly(ethylene oxide). Guar gum, which is a natural polymer - a polysaccharide derived from a plant, gave a similar reduction effect.

Surfactants were discovered as an efficient drag reducer in the early forties. During World War II, Mysels observed a similar drag reduction effect for gasoline thicken with an anionic surfactant, ie. aluminium soaps. The findings of the work were first patented much later in 1949 [8]. Ten years later, knowledge of additives to reduce drag was further advanced by the work of Dodge and Metzner [9], and Shaver and Merrill [10]. Both noticed unusually low friction factors for certain non-Newtonian solutions like those of sodium carboxy methylcellulose in water. Drag reduction has also been reported for several suspensions of insoluble particles such as fine grains [11] or fibres [12, 13] and for microbubles. For passive DR methods, it has been found that modified surfaces, such as compliant surfaces, heated surfaces, and surfaces covered with small triangular ribs aligned with the flow, can provide DR of varying degrees.

Since the subject of DR encompasses a wide range of disciplines including hydrodynamics, fluid mechanics, computing simulation, rheology, polymer science, materials science and chemistry, a large number of papers and reports on DR have appeared in various scientific journals over the years. There are several books [14, 15] and excellent review articles [16-18] relating different aspects of DR. However, due to the multi-disciplinary nature of the subject the books or reviews only focus on a certain area of DR technologies for readers of a particular discipline.

The present review deals with some important DR technologies such as polymers, surfactants, microbubbles and compliant coatings. The pros and cons of each method will be addressed. The review also indicates the state-of-the-art of DR technologies with potential application to submarines.

2. Theory

Drag reduction has been quantified as:

$$\% \, DR = (\Delta P_s - \Delta P_p) \times 100/\Delta P_s \qquad (1)$$

where ΔP_s is the pressure drop in a given length of tube for a pure solvent and ΔP_p is the pressure drop for drag reducing solution with the same flow rate of liquid for both. The pressure loss in a pipe is due to fluid-frictional resistance, broadly classed in terms of laminar and turbulent flows by the fluid Reynolds number. Turbulent flow is defined here in the engineering sense of the flow exceeding a critical Reynolds number (Re), which is for pipes

$$Re = VD/v > 2300 \qquad (2)$$

for an external flow such as over a ship hull

$$Re = VL/v > 500\,000 \qquad (3)$$

and for a rotating disc

$$Re = VR/v > 250\,000 \qquad (4)$$

where V is the flow velocity, for a rotating disc $V = \omega R$ (ω is the angular velocity, R is the radius), D is the pipe diameter, L is the axial length, v is the kinematic viscosity of the drag reducing solution.

DR can be also expressed in terms of friction factor, f. The relationship between f and Re can be expressed by [17],

$$f = 64/Re$$

$$(5)$$

for the laminar regime, and

$$1/(f)^{1/2} = 2 \log_{10} Re \, (f)^{1/2} - 0.8 \qquad (6)$$

for the turbulent flow.

Figure 1 shows a typical relationship between DR and poly(ethylene oxide) (PEO) concentration at a Reynolds number of 14 000 in a small pipe which indicates a flow in the turbulent regime.
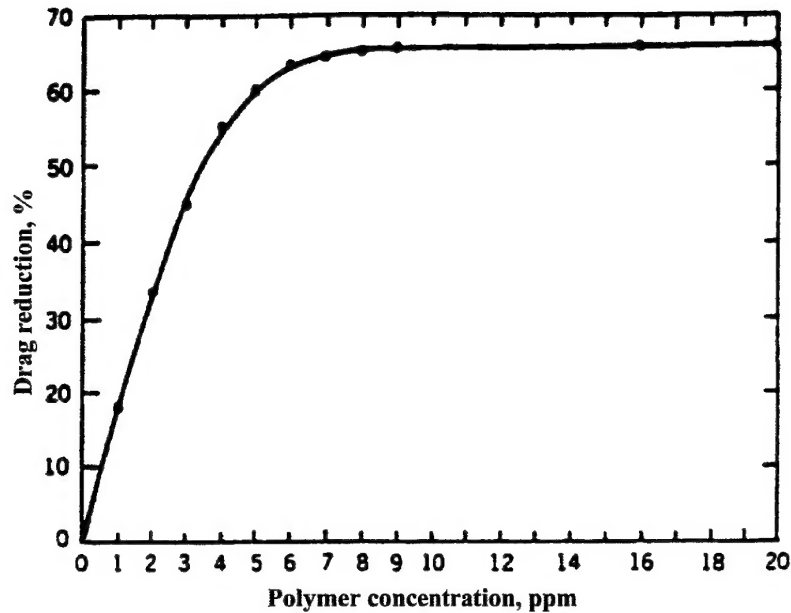
Figure 1: Drag reduction of poly(ethylene oxide) in water, at a Reynolds number of 14000, in a small pipe [17].

Figure 2: Typical data for drag reducing polymer solutions fall between the turbulent friction line for pipe flow, and the laminar line, 64/Re, extended beyond its usual limit of a Reynolds number of 2300, where f = pipe friction coefficient in engineering terms, equal to pressure drop per length times the diameter, divided by ½ρV², and ρ = fluid density [17].

Typical drag reduction data fall between solvent values for laminar flow and the curve for turbulent smooth pipe flow (Figure 2). The effect of drag reduction is to reduc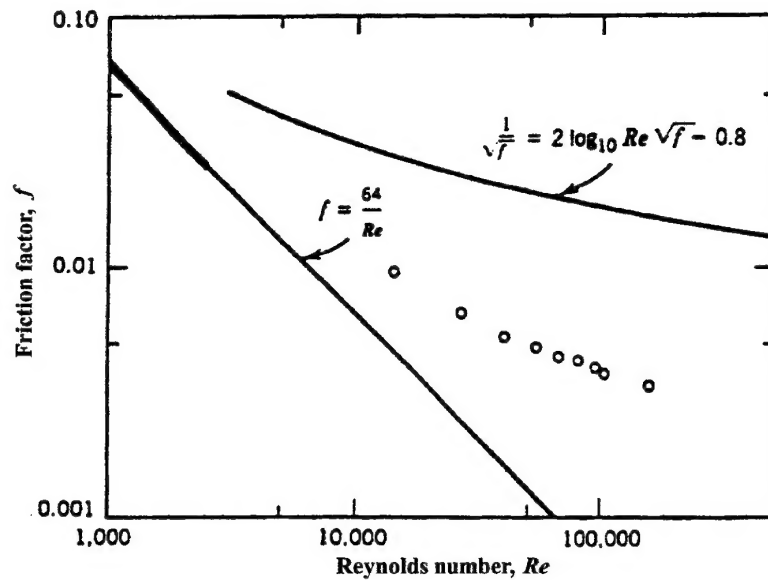e the friction to a value considerably lower than the turbulent flow of the solvent, but not approaching that corresponding to laminar conditions (Figure 2).

3. Drag Reduction with Polymer Solutions

3.1 Overview

To date, polymer solutions are the most widely studied and most often employed of the drag reducing systems. Several typical polymer drag reducing solutions are shown in Table 1

Table 1: Drag reducing polymer solutions

Water-soluble polymers	Solvent-soluble polymers
Poly(ethylene oxide)	Polyisobutylene
Polyacrylamide	Polystyrene
Guar gum	Poly(methyl methacrylate)
Xanthan gum	Polydimethylsiloxane
Carboxymethyl cellulose	Poly(*cis*-isoprene)
Hydroxyethyl cellulose	

Experiments show that the higher the molecular weight (MW), the more effective a given polymer as a drag reducer [17]. Polymers with a MW below 100 000 seem to be ineffective [17]. As the average MW of poly(ethylene oxide) (PEO) is increased from 2×10^5 to above 5×10^6, the solution concentration to achieve about 70 % drag reduction on a rotating disk is reduced from 600 to 100 ppm [17]. In other words, the higher the MW, the greater the drag reduction for a given concentration and Re number. The longer polymer chain provides more chance for entanglement and interaction with the flow. It has been confirmed that the extension of the polymer chain is critical for drag reduction. The most effective drag reducing polymers are essentially in linear structure, with maximum extensivity for a given molecular weight. Poly(ethylene oxide), polyisobutylene and polyacrylamide are typical examples of linear polymers. Polymers lacking linear structure, such as gum arabic and the dextrans, are ineffective for drag reduction [17].

A remarkable aspect of polymers as a drag reducer is that DR occurs at very low concentrations in the ppm region. Increasing the concentration beyond 30 - 40 ppm lowers DR for PEO in a small tube (Figure 1) owing to increase of the viscosity with increasing concentration. Interestingly, DR can be observed in concentration as low as 0.02 ppm [19]. Using a rotating disk apparatus [20] or a rotating cylinder [21], DR

induced by water-soluble polymers (PEO, guar gum) and solvent-soluble polymers (polyisobutylene) showed similar results to the experiments performed with a small tube.

A range of new water-soluble polymers have been synthesized by McCormick and co-worker [22]. They have undertaken extensive analyses of polymers of widely different structures and compositions. These polymers include hydrophobically modified polyacrylamide polymers, anionic and cationic polyelectrolytes and polyampholytes. Applications of these water-soluble polymers to DR technologies have been investigated [18, 23-27]. It was discovered that all copolymers were found to conform a universal curve for DR, when normalized for hydrodynamic volume fraction polymer in solution. This method of plotting allows the comparison of DR efficiencies of polymers of different structures, compositions and molecular weight.

Biopolymers such as high molecular weight polysaccharides produced by living organisms can provide effective DR [16]. Polysaccharides of several fresh water and marine algae, fish slimes, seawater slime and other fresh water biological growths have been found to be good drag reducers. Interestingly, as mentioned later these biological additives are also a source of fouling growth which can substantially reduce the DR effectiveness brought about by other DR technologies.

Kim and coworkers [28-30] investigated the effect of salt water on the DR of water-soluble poly(acrylic acid) (PAA). This work has important implication to the DR effect on submarines. Salt (sodium chloride) enhances the DR efficiency of PAA diluted solution because the salt molecules prevent the aggregation of PAA chains which lower the DR properties of the PAA solution.

3.2 Mechanisms

A number of theories have appeared to explain how polymer molecules interfere with production, growth or transport of turbulent disturbances. The polymer hydrodynamic coil interacts with and disrupts the eddies and micro-vortices present in turbulent flows. These theories explain many of the observed changes in flow structure during drag reduction [31-33]. Tulin [34] proposed that the DR effect seems to depend on the stretching of individual molecules by high strain rates in the flow. At high strain rates, the polymer chain tends to elongate along the principal strain rate axis, and large extensions result. At the same time, a form of strain-rate hardening occurs in which the elongation viscosity becomes very high. As the elongation viscosity increases, the large scale bursts and sweeps in the wall layer flows are inhibited, thus reducing friction [34]

Although many researchers feel that macromolecular extension is involved in turbulence suppression, there is still disagreement on this point [35]. The many facets of DR, eg. the extremely dilute character of the polymer solutions, and the undefined nature of turbulent flow, make it a complex phenomenon to explain. Since DR is characterized by large changes in the flow caused by the presence on a trace of

5

additives, the objective of drag reduction studies is to seek an equally sensitive mechanism which can predict such a large effect at the dilutions involved.

The complexity of the phenomenon has led some researchers to believe that more than one drag reduction must exist. Experimental evidence may be construed to support several theoretical models. It is possible that more than one mechanism may be required to adequately explain the phenomenon.

4. Drag Reduction with Surfactant Solutions

4.1 Overview

Surfactants are surface active agents which are the main constituent in soaps and detergents. Apart from the classical soaps, which are the alkaline salts of higher fat acids, new surfactants have been synthesized over the years, which also consist of a polar (hydrophilic) head and nonpolar (hydrophobic) tail. Depending on the electrical charge of the head group, the surfactants can be classified as anionic, cationic and nonionic. When the concentration of a surfactant solution exceeds a critical value, the surfactant molecules start to form aggregate, ie. micelles. The association of the molecules to micelles is reversible, ie. when the concentration is below the critical value the micelles will dissociate into molecules again. The micelles are always in thermodynamic equilibrium with the molecules, and are of the size of about 20 to 1000 surfactant molecules. Depending on the molecular structure, concentration, type of solvent, three geometrical types of micelles can be distinguished: spheres, rods, and discs. Furthermore, by adding some salts (ie. electrolytes), the electrolytic repulsion forces of the head groups can be suppressed, the molecules can be packed more densely facilitating the formation of disc-like or rod-like micelles. The drag reducing ability of a surfactant solution depends strongly on the shape of these micelles.

Although the effect of surfactant solutions on DR was conducted by Mysels as early as 1949 [8], the research has not been as exhaustive and has received less attention than polymer solutions. It was not until 10 years later that the interest in DR by surfactants was revived by the work of Dodge and Metzner [9], and Shaver and Merrill [10]. Surfactant solutions have become a favourite drag reducer owing to their chemical and mechanical stability that is an important requirement for practical applications. Also, development of surfactant systems exhibiting drag reduction at concentrations similar to dilute polymer solutions (< 100 ppm) have been disclosed in a number of recent patents [14]. Shenoy [16] reviewed the use of surfactant systems for DR. The study compares the DR effectiveness and outlines the morphological differences of micellar and polymeric solutions.

4.2 Anionic Surfactants

Following the pioneering work of Mysels [8] in non-aqueous systems, Savins [36-37] carried out extensive work on anionic surfactants as drag reducers in aqueous solutions. Alkali metal and ammonium soaps were used to obtain a DR of 30 % for 0.2% sodium oleate solutions [36]. Savins also observed that the addition of an electrolyte (eg. KCl) can help to increase the drag reduction. It was explained that KCl helped in the enhancement of the association of the soap molecules and that the soap micelles, which were initially spherical in the aqueous solution, were rearranged under the influence of the electrolyte into cylindrical shapes, which in turn formed a network of interlaced rod-like elements. The soap concentrations involved were of the order of 0.1 %, which are considerably higher than the polymer concentrations.

Savins [36] observed an interesting stress controlled DR effect in the soap solutions. The DR increased with increasing shear stress up to a critical value. Beyond the critical value, the DR of the soap solution became indistinguishable from that of the soap-free solution. This indicates that the network of micelles collapses if the shear stress exceeds a critical shear stress. This occurs because of a temporary disentanglement of the network induced by turbulent vortices and eddies in fully developed flow. If the wall shear stress is reduced from above to below the critical value, then the network bonds reform and the reducing ability of the solution is restored. In contrast, once the polymer chains are broken by high shear stress, the drag reducing ability of the polymer solution is permanently lost. The critical shear stress can be up to 100 Pa, which is quite high in comparison to the wall shear stress where mechanical degradation starts in dilute polymer solutions.

In practice, the utility of anionic surfactants available in industry would meet the requirements of long-term stability of the drag reducing effect. Although these conventional soaps are relatively inexpensive and mechanically stable, they have limited applicability as they are precipitated out by interaction with calcium and other ions that are generally present in tap and sea water.

4.3 Cationic Surfactants

Cetryltrimethylammonium bromide (CTAB) is the cationic surfactant which has been investigated for drag reduction in detail [38]. Gadd [38] suggested the possibility of using the CTAB-naphthol mixture to reduce turbulent friction, because the mixture showed shear-thinning characteristics. Similar to anionic surfactant solutions, the drag reducing ability of the CTAB-naphthol solution terminated at some upper Reynolds number corresponding a critical shear stress where there was a scission of the micelles.

One marked advantage of cationic surfactants over the anionic ones is that these complex soaps do not precipitate in the presence of calcium ions. However, they are expensive and degrade chemically in aqueous solutions in a matter of a few days.

Further, although they are mechanically stable, they are not thermally stable and thus limited in practical applications.

4.4 Nonionic Surfactants

The studies on nonionic surfactants as drag reducers have been reported only by Zakin and Chang [39-40]. They investigated the effect of temperature, electrolyte concentration, surfactant concentration and the effect of mechanical shear on three nonionic surfactants formed from linear alcohols and ethylene oxide moieties. They found that 1% solutions of the commercial surfactants like Alfonic 1214 were more effective than the 0.5 % solutions. The critical shear stress for mechanical degradation in the case of nonionic surfactant is dependent on the surfactant concentration, electrolyte type and concentration, and on the temperature [39-40]. The molecular structure of the surfactant has an important effect on its micelle size and shape which in turn profoundly influence the drag reducing ability [39-40].

Nonionic surfactants have an advantage over the anionic and cationic counterparts because they are both mechanically and chemically stable. They do not precipitate out in the presence of calcium ions and therefore can be used in impure waters, seawater or concentrated brine solutions. Despite these merits, more studies are needed to exploit the potential of nonionic surfactants to their fullest extent as a drag reducer.

4.5 Comparison with Polymer Solutions

Formation of micelles and their shapes are main factors influencing the drag reduction ability of the surfactant solutions. The main characteristics feature of the friction behaviour of surfactant solutions is the disappearance of drag reduction when a critical wall stress is reached [16].

The spherical micelle is generally conceived as a small ball-like particle of colloidal dimensions and fairly constant in size for a given surfactant. These spherical micelles exist only in relative dilute solutions. In concentrated solutions, however, the lamellar micelle is favoured. Under the influence of an electrolyte, spherical micelles can rearrange into cylindrical or rod-like micelles [14, 41].

When one compares the data for surfactant solutions with that for polymer solutions , it becomes obvious that the drag reduction behaviours in these two cases are different. While the soap solution exhibits drag reduction low wall shear stress values, the polymer solutions show relatively small drag reduction at low Reynolds numbers and increasingly large reduction at high Reynolds numbers. These two types of behaviour are obviously a consequence of the morphological difference between micellar and polymeric structures [16]. It can be assumed that: (a) the flexible polymer molecule needs to be elongated by a large velocity gradient before its full drag reducing ability is developed, and (b) the surfactant particles are oriented much more easily at lower velocity gradients, but the micelles collapse at high shear stresses associated with large

velocity gradients [16]. In terms of equivalent molecular weight, micelles are known to have larger values than polymers and therefore they would shift the onset of drag reduction to a lower shear stress value [16, 17].

5. Drag Reduction with Microbubbles

Microbubble-modified boundary layer and associated skin friction reduction have been an active area of research for ship hull in recent years because of its energy saving potential [42-44]. The DR in a turbulent boundary layer on a smooth wall can be realized by reducing the skin friction under suitable conditions when small gas bubbles are injected into the flow from an upstream position [42]. The injection of gas into a liquid turbulent boundary layer to form bubbles reduces skin friction drag locally by as much as 80 %. Although it has long been know that a layer of air next to a surface in water reduces turbulent skin friction, the concept of the microbubble-modified boundary layer came into existence in its present form from the pioneering work of McCormick and Bhattacharyya [45]. They used a copper wire wound around a towed body of revolution to produce hydrogen bubbles by electrolysis. Their experiments showed that microbubbles could reduce total drag and that the DR increased with increasing gas generation rate and decreasing rate. The results, however, were limited to Reynolds numbers between 0.3 and 1.8 million. Subsequently, several experiments conducted in the former Soviet Union reported significant drag reduction in water tunnel boundary layers by injection of air bubbles through flush-mounted porous plates [46-47]. In the 1980s, through a series of systematic studies in water tunnels the drag reducing effects on flat wall by microbubbles generated by porous plates [48-51] and on axisymmetric body by circumferential porous rings [52-53] were observed. Recently, Kato et al [55-56] carried out several experiments with microbubbles in a flat plate boundary layer. In order to overcome the practical limitations of conventional porous plates, such as high injection energy and marine biofouling when used below a ship hull, a new injection method using a slit was devised [56].

Merkle and Deutsch [57] indicated that the size of the bubbles is clearly a parameter of importance. The diameters of the bubbles affect their trajectories and thus their concentration and location in the boundary layer. Measurements of bubble sizes indicate that the bubble size decreases when free stream speed is increased and increases when airflow rate is increased, but appears to show little dependence on the injection procedure [57]. The bubble sizes in a microbubble cloud are subject to any of three competing mechanisms: the initial formation at the wall; bubble splitting by turbulence action and bubble coalescence upon collision. The most significant characteristic of the bubble sizes is their diameter in comparison to the boundary layer scales. Merkle and Deutsch [57] showed that the bubble sizes (500 – 1200 μm) appear to range between an order of magnitude larger than the sublayer thickness (about 10 μm) and an order of magnitude smaller than the boundary layer (about 10 mm). Because of a wide range of the sizes, fairly substantial changes in bubble size are needed to alter the manner in which the bubbles interact with the boundary layer. However, such

dramatic changes in bubble size may be quite difficult to accomplish. Possibilities for controlling bubble sizes and trajectories and ultimately for optimizing gas flow requirements remain high priority items in microbubble research.

Although the effectiveness of microbubbles has been demonstrated and the bubble sizes have been found to be one of the important factors affecting the DR, the over all mechanism that leads to this reduction is only poorly understood. In particular, the interaction between the bubbles and the boundary layer has not been studied extensively [58]. Guin et al [59] investigated the DR effects due to the introduction of microbubbles into a two-dimensional water channel. The study established a relationship between the DR effectiveness and the near-wall bubble concentration. Pal et al found that the bubbles was effective for drag reduction if they are located beyond a certain distance from the wall [50]. The data of Guin et al [58] not only support their finding, but also provide some quantitative relation between drag reduction and near-wall void fraction. Numerical investigations into the mechanisms of microbubble drag reduction have been conducted by Madavan et al [60]. The action of the bubbles is simulated by allowing the viscosity and density to vary locally as a function of a prescribed bubble concentration profile. The results of the model show that substantial skin friction reductions can be obtained when microbubbles are present, thus supporting the idea that microbubbles can act not only as an agent to reduce skin friction, but also to reduce overall drag

Madavan et al [60, 61] compared the mechanism for microbubble drag reduction to that for polymer reduction. They showed that microbubbles can interact with the turbulent flow in the buffer layer to cause changes in the order of unity in the skin friction. In this respect their effect seems to be closely related to that achieved by polymer additives. Like polymer solutions, microbubbles appear to destroy the energy producing fluctuations near the buffer region. The resulting growth of the sublayer thickness is a manifestation of the drag reduction [60]. Both polymer solutions and microbubbles appear to have very strong effects on dynamics of turbulence for drag reductions greater than about 40 % [60].

Application of air injection along the along the bottom of the hull to reduce the skin friction was proposed as early as the beginning of this century. River barges and ship fitted with an air injection system showed 10 – 15 % reduction in skin friction [44].

6. Compliant Coatings

6.1 Overview

Cetaceans seem to possess unusually low overall drag coefficients. Observation of the amazing swimming abilities of the dolphin led Kramer [62, 63] to design his first compliant coatings. Kramer claimed that his invention of a compliant coating reduces drag by up to 60 %. Kramer conducted his original experiments by towing a model

behind an outboard motor boat. A typical successful coating giving at least 50 % DR designed by Kramer consisted of a flexible inner skin, an outer diaphragm, and stubs, all made of soft natural rubber. The cavity between the outer diaphragm and the inner skin was usually filled with a highly viscous damping fluid. As his preliminary experiment indicated, the drag reduction was attributed to the delay of the transition of laminar-turbulent boundary layer to higher Reynolds number compared to that on a rigid wall.

After Kramer's original publications in 1957 and 1960 [62, 63], DR with compliant coatings has become a popular topic of research. Several investigations [64, 65] were conducted to duplicate Kramer's coating and his results, but no significant drag reduction was observed in any of these investigations. Since then, researchers have assumed that Kramer's results were in error and that his observations could have come about as a result of accidental excretion of the silicone oil used as the damping fluid during the tests. Although theoretical models have indicated that it is possible to stabilize a laminar boundary layer and to delay the transition of laminar-turbulent flows indefinitely with appropriate flexible materials, experiments with compliant wall models in water and air flows have produced no conclusive data [66]. During the 1970s various compliant materials were tested in water at the Naval Ocean Systems Center, the Naval Research Laboratory and the Naval Undersea Warfare Center [67]. In each case, no statistically significant reduction in drag was measured.

It was not until 1985 when careful analyses by Carpenter and Garrard [68] and well-controlled experiments by Gaster [69] that, for the first time, provided direct confirmation of the transition delaying potential of compliant coatings. These vindicated Kramer's original claims, and offered a plausible explanation for the failure of the subsequent laboratory experiments. It was shown that transition Reynolds numbers, which exceed by an order of magnitude those on rigid surface boundary layers, can be achieved.

6.2 Coating Optimization

The following considerations should be made, if a compliant coating is to be designed for use on a vehicle [70]:

(1) What limits the transition-delaying performance of a compliant wall?
(2) What is greatest possible transition delay achievable?
(3) What are the optimum wall properties to give the greatest transition delay?

These questions have been addressed [71, 72] for the plate-spring compliant wall originally introduced by Carpenter and Garrard [68] as a theoretical model of the Kramer coating. In the past, there was a rule of thumb: "If it is soft, let us try it" [67]. A wall that is too compliant (ie. too soft) can substantially delay transition, but rapid breakdown can occur through the amplification of wall based instabilities. A different type of compliant wall (Figure 3) comprises a soft viscoelastic substrate surmounted by

a thin, much stiffer outer layer [70]. Such walls are simpler to manufacture and are regarded as more practical. Carpenter [72] suggested that a multiple-panel coating, placed in series, with each panel optimized for a particular range of Reynolds numbers, is likely to produce larger transition delays than a single-panel coating.
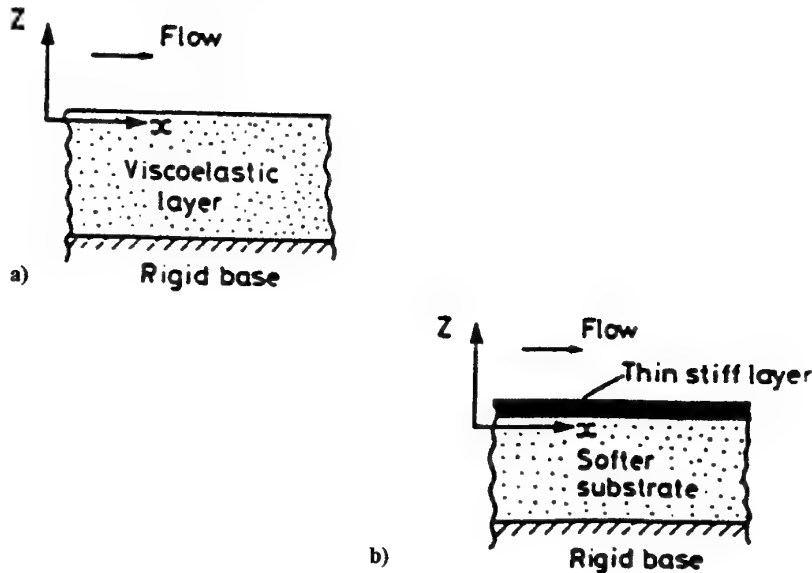

Figure 3: Schematic of the compliant wall, a) single layer and b) double layer [70].

Chung [66] devised a composite compliant coating that can reduce the skin friction on a rotating disc up to 21% at the Reynolds number of 8.92 x 10⁵. The coating was fabricated out of four major components (Figure 4): (1) a thin stiff film as the top layer, (2) a low modulus high damping silicone elastomer as a thin layer embedded on (3) the rayon fabric, and (4) a support screen. The stiffness of the top film greatly influenced the performance of the coating. The use of a Teflon film (0.13 mm thick) led to the best result for Chung's work in the Reynolds number range of 8.92 x 10⁵ to 1.94 x 10⁶. Chung [66] postulated that the top film helps reduce skin-friction due to (1) top film stabilizes the compliant surface from forming static divergence which increases skin-friction drastically, and (2) the high modulus film may be resonant to the turbulent fluctuations at high frequencies which helps the coating to reduce the skin-friction in the turbulent boundary layer. Chung concluded that high loss tangent reduces the skin-friction more effectively than a low damping coating.

Many theoretical studies have shown that the turbulent-laminar transition can be delayed through the attenuation of so called "Tollmien-Schlichting waves" (TSW) [73]. The early work of Benjamin [73] and Landahl [74] showed that as the compliance characteristics of a coating is increases the growth of the TSW is progressively suppressed. Theoretically, if the coating were to be made sufficiently compliant the TSW would be completely stabilized resulting in the maintenance of laminar flow for

indefinitely high Reynolds numbers. Optimization of viscoelastic compliant coatings has been theoretically examined by Dixon et al [70]. These authors determined the best transition-delaying performance possible using compliant coatings made from viscoelastic materials.
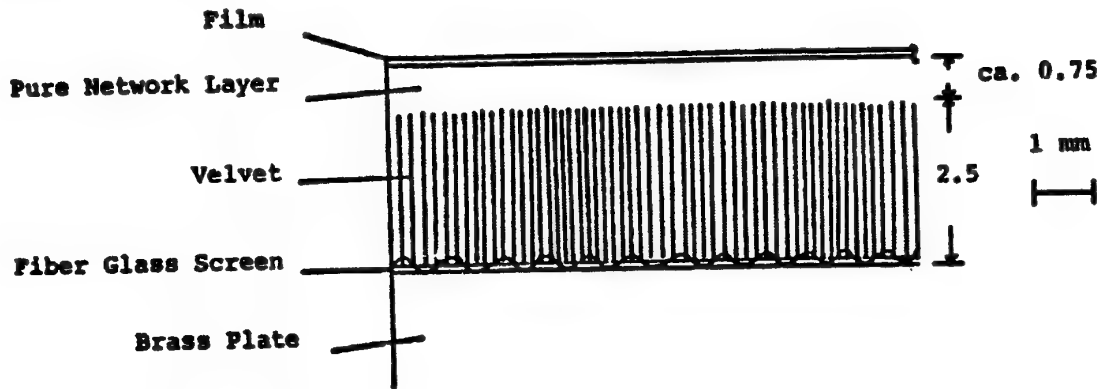
Figure 4: Detail of compliant coating [66].

6.3 Future Development

It has been more than 40 years since Kramer first disclosed his well-known experiment using a compliant coating. The general acceptance of the validity of his finding and therefore the enthusiasm towards the research on the use of compliant coatings have waxed and waned several times since then. The last two decades witnessed renewed interest in compliant coatings as a passive method of drag reduction [67]. Following Kramer's experiment [62, 63], significant advances were made in numerical and analytical techniques to solve the interactions between fluid and structures. Design of the compliant coatings therefore can be optimized or guided by theoretical calculations. Research experience indicates that designing a compliant coating by a "hit or miss" approach is a very inefficient use of limited resources and will perhaps never work.

Interestingly, calculations of the drag reduction using a compliant coating indicates that there is no significant benefit on a large vehicle such as submarines but the coatings can reduce the drag for smaller objects [67]. Nevertheless, a particular location of the submarine hull can be applied with the compliant coatings to enhance the performance of sonar systems.

7. Drag Reduction with Hybrid Methods

Since there are a number of drag reducing methods, the combination of different means is an intuitive development to explore a synergy. Although the combination of

different methods can lead to good results, there are few combined method investigated. Some typical hybrid methods will be described in this section.

7.1 Joint Action of Polymers and Microbubbles

The ability to increase DR beyond the sum of the individual components, thereby creating a synergistic effect, implies that bubbles may promote the elongation of polymer chains and/or that polymers enhance the concentration of small bubbles near the wall. Malyuga et al and Philips et al [75, 76] found that there was a mutual intensification of polymers and microbubbles for drag reduction. They attributed this effect mostly to the greater concentration of small diameter bubbles when the polymer solution was aerated just prior to injection. Also, polymers in flow prevent the bubble coalescence and impede bubble rising. They noted that the drag reduction levels attained by aerating the polymer solution would exceed reduced drag levels measured with only air or only polymer injection into the boundary layer.

If the combination of polymer and microbubbles can reduce the volume of gas and/or polymer solution required to maintain desired levels of drag, these two robust techniques become much more attractive for undersea applications. Phillips et al [76] found when the order of injection was microbubbles upstream and polymer downstream there were clear cases of synergy. The total effectiveness of the two individual methods can be enhanced by 10 % due to synergy by adjusting the polymer flow rate and the microbubble flow rate.

7.2 Joint Action of Compliant Coatings and Polymers

Semenov [77] carried out a comprehensive study to investigate the combination effect of compliant coatings and polymers. The polymer in their study was PEO. Depending on the PEO concentrations, the thickness of the coating, the coating materials and the speed of the tested object, three cases can be observed:

$$\psi_{CP} = \psi_C + \psi_P \tag{7}$$

$$\psi_{CP} < \psi_C + \psi_P \tag{8}$$

$$\psi_{CP} > \psi_C + \psi_P \tag{9}$$

where ψ_{CP}, ψ_C and ψ_P are the drag reduction efficiency of the combined method, that of the compliant coating and that of the polymer, respectively.

7.3 Joint Action of Compliant Coatings, Microbubbles and Polymers

The combination of compliant coatings, microbubbles and polymers can suppress the turbulent wall-pressure fluctuations in a wide range of frequencies. Therefore, it is

envisaged that these combinations would lead to substantial decrease of the hydrodynamic noise in a wide frequency band [77].

7.4 Joint Action of Compliant Coating and Microbubbles

Semenov et al [77] investigated the joint action of compliant coating and microbubbles. Since the total efficiency of drag reduction is equal to the sum of individual efficiencies, there was no synergy observed.

8. Electromagnetic Turbulence Control and Biofouling Control

8.1 Electromagnetic Turbulence Control (EMTC)

Research on EMTC is being conducted in the next generation of US Navy nuclear-powered attack submarines [78]. The principle of EMTC is based on the electromagnetic force (Lorenz force) induced by an electromagnetic field. The force acts on a flowing electrically fluid (seawater) to produce DR effect [79]. The complicated interactions between the Lorenz forces and flow turbulence have been theoretically and experimentally investigated [79-80]. In practice, EMTC panels or fabrics can be placed on the body of a submarine to prevent the start of processes that produce turbulence. The research on EMTC is still at an embryonic state, but it can be a promising technology effectively reducing acoustic signature, increasing speed and manoeuvrability [78].

8.2 Biofouling Control

Biofouling control is a vital part of any DR projects. The fouling layer consisted of slimes and small barnacles on a tested towing tank was found to cause a four-fold increase in resistance comparing with the original clean state [81]. Many toxic antifouling paints have been used in the past, but non-toxic hydrodynamically self-cleaning coatings with a low surface energy is now a reality. The remaining challenge is to improve application and durability. Furthermore, Candries et al [82] recently pointed out that in addition to the surface energy the Young's modulus and the thickness of the coating affect the adhesion of marine organisms to a surface. Although the antifouling coatings may maintain the DR effectiveness in a long term, how the antifouling coatings affect the near-wall turbulence flow and therefore the effectiveness of drag reducers is still unknown.

9. Applications to Submarines

Intensive research on DR using several techniques in the past several decade has been paid off with several successes. For example, reduced drag can provide increased range or increased speed in nearly any transportation system or can result in fuel savings [42, 44]. Water-soluble polymers, surfactants microbubbles have been tested on ship hull with success. While Latorre [44] could achieve 10 – 15 % DR for ship, greater DR can be reached with a system developed by Mitsui Engineering & Shipbuilding Co. In this system, the bottom of the ship is coated with a highly water-repellent paint and air is supplied by a compressor (Figure 5) [43].
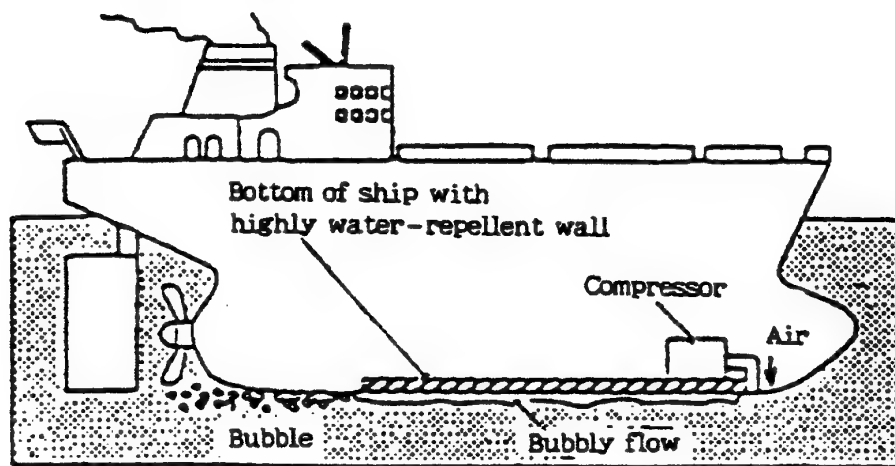

Figure 5: Model of drag reduction systems for a ship [43].

These DR methods have been applied to submarines and torpedoes. However, due to the secret nature of the work there are few results in the open literature. A general description of the work on submarines can found in popular scientific magazine [83]. Turbulent flows over the surface of a submarine affect its acoustic signature, its endurance and impair the ability of the operators to resolve the incoming signals against the self-noise of the submarine. The US Navy has performed a full-scale testing using polymer ejection [84]. The results showed that polymer ejection can reduce the self-noise of a submarine and decrease the drag of the hull and the radiated noise generated by the propulsor. Speed increases of 10 to 15 % and reduction in self-noise exceeding 10 dB at certain frequencies are possible. Polymer ejection can be deployed locally to improve sensor performance and reduce signal processing requirements.

Although the application of DR technologies to submarines have been actively conducted for the last four decades in the US and former Soviet Union, similar research activities have not been performed in Australia. The DR technologies are so complex that even though the research has lasted for several decades many problems remain to

be solved [84]. Applied and basic research on flow, turbulence and DR has been actively conducted in several research centres in American universities, NUWC (USA) , NSWC (USA) and ERCOFTAC (European Research Community on Flow, Turbulence and Combustion). As an indication of the interest, an international symposium which was organized on 22 –23 July 1998 at the Naval Undersea Warfare Center (Newport, Rhode Island, USA) has attracted more than 70 papers [85].

Several well-known research groups in Australian universities are active in hydrodynamics, fluid mechanics and rheology. A group at Monash University has been involved in DR technologies investigating the effect of polymers on DR in kerosene. However, the effect of DR on the performance of the sonar systems and how to control the growth of biofouling that increases the friction of the ship hull have not been investigated in Australia. Technology base information on DR technologies with application to submarines is extremely important in acoustic signature management for submarines. A systematic approach is important in designing a long term investigation within DSTO, as the research on DR technologies is extremely complex in theory and challenging in practical applications, and is multidisciplinary involving hydrodynamics, materials science, physics and chemistry.

10. DSTO Technical Background and Proposed Research Directions

DR offers several operational and tactical advantages for the Collins Class submarine, since DR delay the transition from laminar flow to turbulent flow when speed is increased. Turbulent flows increase the submarine's acoustic signature and reduce the ability of the operators to resolve incoming signals against the background of the submarine self-noise. DR enables the maximization of the capability of the sonar systems and platform endurance, while retaining low acoustic self-signature.

MPD has a strong foundation in organic materials research that can provide essential knowledge on the use of polymers and surfactants as drag reducers. MOD and the Noise and Vibration group in MPD have developed techniques to monitor the noise and vibration form submarines. Antifouling has also been investigated in MPD. Research on fluid dynamics of air and seawater has been conducted within AOD and MOD for some times with specific application on aircraft and submarines.

If DSTO is required to proceed further in the development of a technology base in the DR area, the following order is proposed to conduct the research taking into account DSTO expertise and resources. Considering the destructive drag effect of biofouling, the first step would be to optimize the antifouling coating systems before introducing complex DR technologies [82, 86]. Second, while release of polymers or surfactants as a drag reducer can give adverse environmental impacts, injection can be confined to the areas where sensors and sonar systems are attached to provide important information

on the performance of these systems. Third, microbubbles are "green" substance to be reckoned for testing. However, precise tooling is required for manufacturing a microbubble releaser with a capability of controlling bubble sizes down to micrometres. Fourth, compliant coatings are an interesting concept, but optimisation of a compliance coating itself or a coating with a dual function of compliancy and antifouling would be a challenging topic for long-term research.

11. References

1. BA Toms, Proceedings of International Congress on Rheology, Vol. II, pp. 135, North Holland, Amsterdam (1949).
2. GT Pruitt and HR Craw, Westco Research Final Report on Contract 60530-8250 to Naval Ordinance Test Station (1963).
3. JG Savins, Soc. Petrol. Eng. 4, 203 (1964).
4. JW Hoyt and AG Fabula, Proceedings – 10th International Towing Tank Conference, Teddington (1963).
5. JW Hoyt and AG Fabula, Proceedings – 5th Symposium on Naval Hydrodynamics, Bergen, Norway, Office of Naval Research ACR-112, 947 (1964).
6. AG Fabula, JW Hoyt and HR Crawford, Bull. Am. Phys. Soc. 8 (1963).
7. JW Hoyt, Trans. Am. Soc. Mech. Engrs, J. Basic Engng 94, 258 (1972)
8. KJ Mysels, US Patent 2 492 173 (1949).
9. DW Dodge and AB Metzner, AIChE J. 5, 189 (1959).
10. RG Shaver and EW Merrill, AIChE J., 5, 181 (1959).
11. RS Kane, in "Viscous drag reduction in boundary layers" (ed. DM Bushnell and JN Hefner) Progress in Astronautics and Areonautics 123, p. 433 (1990).
12. I Radin, JL Zakin and GK Patterson, AIChE J., 21, 358 (1975).
13. HD Ellis, Nature 226, 352 (1970).
14. A Gyr and H-W Bewersdorff, "Drag reduction of turbulent flows by additives", Kluwer Academic (1995).
15. DM Bushnell and JN Hefner (ed.), "Viscous drag reduction", Progress in Astronautics and Aeronautics, vol. 23 (1991).
16. AV Shenoy, Colloid & Polym. Sci., 262, 319 (1984)
17. JW Hoyt, "Drag reduction", in Encyclopedia of Polymer Science and Engineering, vol. 5, 1986.
18. SE Morgan and CL McCormick, Prog. Polym. Sci., 15, 507 (1990).
19. DR Oliver and SI Bakhtiyarov, J. Non-Newtonian Fluid Mech. 12, 113 (1983).
20. HJ Choi and MS Jhon, Ind. Eng. Chem. Res 35, 2993 (1996).
21. E Bilgen and R Boulos, Trans. of the CSME 1, 25 (1972).
22. CL McCormick, J Block and DN Schulz, "Water-Soluble Polymers", in Encyclopedia of Polymer Science and Engineering, vol. 17 (1986).
23. CL McCormick, RD Hester, SE Morgan and AM Safieddine, Macromolecules 23, 2124 (1990).

24. CL McCormick, SE Morgan and RD Hester, ACS Symposium Series, Vol. 467, 320 (1991).

25. PS Mumick, PM Welch, LC Salazar and CL McCormick, Macromolecules 27, 323 (1994).

26. PS Mumick and CL McCormick, Polym. Eng. Sci. 34, 1419 (1994).

27. PS Mumick RD Hester and CL McCormick, Polym. Eng. Sci. 34, 1429 (1994).

28. OK Kim, LS Choi. T Long and TH Yoon, Polym. Comm. 29, 168 (1988).

29. OK Kim, LS Choi, T Long, K McGrath, JP Armistead and TH Yoon, Marcromolecules 26, 379 (1993).

30. OK Kim and LS Choi, "Drag-Reducing Polymers" in Polymeric Materials Encyclopedia (JC Solomone eds), CRC Publishers (1996).

31. A Peterlin, Nature 227, 598 (1970).

32. RJ Gordon, Nature 227, 599 (1970).

33. RJ Gordon, J. Appl. Polym. Sci. 14, 2097 (1970).

34. MP Tulin, in "Proceedings of the 3rd International Conference on Drag Reduction" (RHJ Sellin and RT Moses, eds), Bristol, UK, University of Bristol, Bristol, UK (1984).

35. NS Berman, "The influence of polymer additives on velocity and temperature fields" (B Gambert ed.), p 293, Springer-Verlag, Berlin (1985).

36. JG Savins, Rheol. Acta. 6, 323 (1967).

37. JG Savins, US Patent 3 361 213 (1968).

38. GE Gadd, Nature 212, 1348 (1966).

39. JL Zakin and JL Chang, Nature Phys. Sci. 239, 26 (1972).

40. JL Zakin and JL Chang, Proc. Inter. Conf. on Drag Reduction, Cambridge, UK (1974).

41. DH Everett, "Basic principles of colloid science", The Royal Society of Chemistry (1994).

42. M Tsutahara and M Sakamoto, Trans. of the JSME Series B 61, 2088 (1995)

43. K Watanabe, in "Proceedings of the International Symposium on Seawater Drag Reduction", Newport Rhode Island, pp. 19 (July 1998).

44. R Latorre, Ocean Engng. 24, 161 (1997).

45. ME McCormick and R Bhattacharyya, Nav. Eng. J. 85, 11 (1973).

46. VG Bodgevich, AR Evseev and AG Malyuga, Second International Conference on Drag Reduction, Cambridge (England), BHRA, P. 25 (1977).

47. CL Merkle and S Deutsch, in "Frontiers in experimental fluid mechanics" vol. 46 (M Gad-el-Hak, ed), pp 291 (1989).

48. NK Madavan, S Deutsch and CL Merkle, Phys. Fluids 27, 356 (1984).

49. NK Madavan, S Deutsch and CL Merkle, J. Fluid Mech. 156, 237 (1985).

50. S Pal, CL Merkle and S Deutsch, Phys. Fluids 31, 744 (1988).

51. S Pal, S Deutsch and CL Merkle, Phys. Fluids A1, 1360 (1989).

52. S Deutsch and J Castano, Phys. Fluids 29, 3590 (1986).

53. S Deutsch and S Pal, Phys. Fluids A2, 2943 (1990).

54. H Clark and S Deuthsch, Phys. Fluids A3, 2140 (1991).

55. H Kato, M Miyanaga and Y Haramoto, in "Cavitation and gas-liquid flow in fluid machinery and devices" (TJ O'Hern, JH Kim, WB Morgan eds), FED vol 190, ASME, New York, p. 185 (1994).

56. H Kato, M Miyanaga and H Yamaguchi, in "Advances in multiphase flow" (A Serizawa, T Fukano and J Bataille eds.), Proceedings of the Second International Conference on Multiphase Flow, Kyoto, Elsevier, Amsterdam, p 85 (1995).

57. CL Merkle and S Deutsch, in "Experimental Fluid Mechanics, Lecture Notes in Engineering" (M Gad-el-Haq eds) vol.46, Springer-Verlag, Berlin, pp. 291 (1989).

58. MM Guin, H Kato and Y Takahashi, in "Proceedings of the International Symposium on Seawater Drag Reduction", Newport, Rhode Island, pp. 155 (July 1998).

59. MM Guin, H Kato, H Yamaguchi, M Maeda and M Miyanaga, J. Mar. Sc. Technol. 1, 241 (1996).

60. NK Madavan, CL Merkle and S Deutsch, Trans. Of the ASME, 107, 370 (1985).

61. NK Madavan, S Deutsch and CL Merkle, AIAA Paper 84-0348 (1984).

62. MO Kramer, J. Aero. Sci. 24, 459 (1957).

63. MO Kramer, J. Amer. Soc. Naval Engrs. 72, 25 (1960).

64. S Taneda and H Honji, Report of Research Institute of Applied Mechanics 15, 1 (1967).

65. PBS Lissaman and GL Harris, AIAA Paper No. 69-164 (1969).

66. KH Chung, PhD Thesis "Composite compliant coatings for drag reduction utilizing low modulus high damping silicone rubber" (1985).

67. M Gad-el-Hak, Appl. Mech. Rev. 49, S147 (1996).

68. PW Carpenter and AD Garrard, J. Fluid Mech. 155, 465 (1985).

69. M Gaster, in "Turbulence Management and Relaminarisation" (HW Liepmann and R Narasimha eds), Springer-Verlag, Berlin, p. 285 (1988).

70. AE Dixon, AD Lucey and PW Carpenter, AIAA Journal 32, 256 (1994).

71. PW Carpenter and PJ Morris, J. Fluid. Mech. 218, 172 (1990).

72. PW Carpenter, AIAA Journal 31, 1187 (1993).

73. TB Benjamin, J. Fluid. Mech. 9, 513 (1960).

74. MT Landahl, J. Fluid. Mech. 13, 609 (1962).

75. A Malyuga, V Mikuta and A Nenashev, in "Proceedings of the 18th Scientific & Methodological Seminar on Ship hydrodynamics, Varna (Bulgaria), pp. 74-1 (September 1989).

76. RB Phillips, JM Castano and J Stace, , in "Proceedings of the International Symposium on Seawater Drag Reduction", Newport, Rhode Island, pp. 335 (July 1998).

77. BN Semenov, in "Proceedings of the International Symposium on Seawater Drag Reduction", Newport, Rhode Island, pp. 269 (July 1998).

78. D Foxwell, Jane's Navy International, pp. 4 (July/August 1998).

79. A Tsinober, in "Viscous drag reduction in boundary layers" (ed. DM Bushnell and JN Hefner) Progress in Astronautics and Areonautics 123, pp. 327 (1990).

80.   Chapter "Turbulent Drag Reduction Methods: Electromagnetic Drag Reduction" in "Proceedings of the International Symposium on Seawater Drag Reduction", Newport, Rhode Island, pp. 359 (July 1998).

81.   G Swain, in "Proceedings of the International Symposium on Seawater Drag Reduction", Newport, Rhode Island, pp. 155 (July 1998).

82.   M Candries, CD Anderson and M Altar, J. Protective Coatings and Linings 18, 38 (2001).

83.   M W Browne, Discover, pp. 67 (April 1984).

84.   "Technology for the United States Navy and Marine Corps, 2000-2035", Naval Studies   Board,   National   Research   Council,   in http://www2.nas.edu/nsb/tfnf.htm

85.   "Proceedings of the International Symposium on Seawater Drag Reduction", Newport, Rhode Island, pp. 155 (July 1998).

86.   JA Lewis, DSTO Maritime Platforms Division, private communication.

Director General Defence Knowledge Improvement Team (DGDKNIT) R1-3-A141, CANBERRA ACT 2600 (Doc Data Sheet only)

Navy

SO (SCIENCE), COMAUSNAVSURFGRP, BLD 95, Garden Island, Locked Bag 12, PYRMONT NSW 2009 (Doc Data Sheet and distribution list only)

Army

Stuart Schnaars, ABCA Standardisation Officer, Tobruk Barracks, Puckapunyal, 3662(4 copies)

SO (Science), Deployable Joint Force Headquarters (DJFHQ) (L), MILPO Gallipoli Barracks, Enoggera QLD 4052 (Doc Data Sheet only)

NPOC QWG Engineer NBCD Combat Development Wing, Tobruk Barracks, Puckapunyal, 3662 (Doc Data Sheet relating to NBCD matters only)

Intelligence Program

DGSTA Defence Intelligence Organisation

Manager, Information Centre, Defence Intelligence Organisation

Corporate Support Program

Library Manager, DLS-Canberra

UNIVERSITIES AND COLLEGES

Australian Defence Force Academy
   Library
   Head of Aerospace and Mechanical Engineering
Hargrave Library, Monash University (Doc Data Sheet only)
Librarian, Flinders University

OTHER ORGANISATIONS

NASA (Canberra)
AusInfo

<div align="center">

OUTSIDE AUSTRALIA

</div>

ABSTRACTING AND INFORMATION ORGANISATIONS

Library, Chemical Abstracts Reference Service
Engineering Societies Library, US
Materials Information, Cambridge Scientific Abstracts, US
Documents Librarian, The Center for Research Libraries, US

INFORMATION EXCHANGE AGREEMENT PARTNERS

Acquisitions Unit, Science Reference and Information Service, UK
Library - Exchange Desk, National Institute of Standards and Technology, US

SPARES (5 copies)

Total number of copies: 42

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION DOCUMENT CONTROL DATA	1. PRIVACY MARKING/CAVEAT (OF DOCUMENT)

2. TITLE Drag Reduction Technologies (U)	3. SECURITY CLASSIFICATION (FOR UNCLASSIFIED REPORTS THAT ARE LIMITED RELEASE USE (L) NEXT TO DOCUMENT CLASSIFICATION) Document (U) Title (U) Abstract (U)

4. AUTHOR(S) V.-T. Truong	5. CORPORATE AUTHOR Aeronautical and Maritime Research Laboratory 506 Lorimer St Fishermans Bend Vic 3207 Australia

6a. DSTO NUMBER DSTO-GD-0290	6b. AR NUMBER AR-011-925	6c. TYPE OF REPORT General Document	7. DOCUMENT DATE June 2001

8. FILE NUMBER 510/207/1156	9. TASK NUMBER DST 99/110	10. TASK SPONSOR DSTO	11. NO. OF PAGES 22	12. NO. OF REFERENCES 86

13. URL on the World Wide Web http://www.dsto.defence.gov.au/corporate/reports/DSTO-GD-0290.pdf	14. RELEASE AUTHORITY Chief, Maritime Platforms Division

15. SECONDARY RELEASE STATEMENT OF THIS DOCUMENT

Approved for public release

OVERSEAS ENQUIRIES OUTSIDE STATED LIMITATIONS SHOULD BE REFERRED THROUGH DOCUMENT EXCHANGE, PO BOX 1500, SALISBURY, SA 5108

16. DELIBERATE ANNOUNCEMENT

No Limitations

17. CASUAL ANNOUNCEMENT	Yes

18. DEFTEST DESCRIPTORS

Drag reduction, Polymers, Surfactants, Coatings.

19. ABSTRACT
Diluted polymer solutions, surfactants, microbubbles and compliant coating as drag reducers have been reviewed in this report. The advantages and disadvantages of each method have been discussed. For the polymer solutions, it is possible to achieve up to 80 % drag reduction with only a few parts per million of polymer. Ionic and non-ionic surfactants can also offer similar drag reduction as polymer solutions but at a high concentration of few percent. Microbubbles are perhaps the cheapest and non-polluted drag reducer. However, the control of the bubble size and the angle of ejection can impose technical challenges. This method can be combined with other drag reduction (DR) technologies such as polymers to enhance its effectiveness. Compliant coatings can be designed to behave in a similar fashion to the skin of a dolphin. The development of the compliant coating is theoretically complicated, although the optimized coating can offer a DR up to 50 %. Despite the extensive research in the area of DR over the past four decades, for each DR technology there is no universally accepted model that explains the DR mechanism. Application of DR technology with microbubbles to the ship hull indicated a 10 – 15 % reduction in drag. The full scale testing of a submarine by the US Navy has shown that polymer ejection has the potential to reduce the self-noise, drag and radiated noise generated by the propellor.